Designing a Geospatial Information Infrastructure for Mitigation of Heat Wave Hazards in Urban Areas

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Abstract: Extreme heat is a natural hazard that could rapidly increase in magnitude in the 21st century. The combination of increasing urbanization, growing numbers of vulnerable people, and the evidence of global warming indicate an urgent need for improved heat-wave mitigation and response systems. A review of the literature on heat-wave impacts in urban environments and on human health reveals opportunities for improved synthesis, integration, and sharing of information resources that relate to the spatial and temporal nature of threats posed by extreme heat. This paper illustrates how geospatial technologies can aid in the mitigation of urban heat waves.

DOI: 10.1061/(ASCE)1527-6988(2004)5:3(147)

CE Database subject headings: Urban areas; Health hazards; Geographic information systems; Remote sensing; Temperature.

Introduction

Cities and climate are coevolving in a manner that could place more vulnerable populations at risk from exposure to extreme heat. Throughout the world, the 21st century will be the first period of time in recent history with more people living in urban areas than in rural areas. In the United States, for example, the urban population already comprises nearly two-thirds of the country's total population and is likely to continue to grow (U.S. Census Bureau 2000). Throughout much of human history, cities have been catalysts for civilizations and nations to become more wealthy, healthy, and rich in culture and knowledge. However, with an increasing number of urban inhabitants, especially vulnerable groups such as the elderly and children, management of urban health, sustainability, and quality of life is a continuing challenge.

Global urbanization and its associated industrialization exacerbates concentrations of greenhouse gases and other atmospheric constituents, which alter the global climate system. Largely because of that, the 21st century is expected to be characterized by global warming (IPCC 2001). According to scientific predictions, global climate change will likely lead to increases in the frequency, duration, and magnitude of heat waves (Kattenberg et al. 1996; IPCC 2001).

The rapid growth of urban population, the urban heat island effect, and a potential increase in the frequency and duration of heat waves due to global climate change, raise a series of issues about the increased health risks of sensitive urban populations to extreme heat and the effective means of mitigating impacts of heat waves. The underlying assumption of this study is that an inadequate understanding of the geospatial nature of vulnerable populations and their surroundings limits the design of efficient and effective strategies for reducing human health threats posed by extreme heat events in cities.

The goal of this paper is to evaluate how geospatial technologies can enhance understanding and improve mitigation of heat-wave impacts in urban areas. First, we summarize research on heat-wave impacts, urban heat island effect, and factors of societal vulnerability to extreme heat. We then review heat-wave mitigation strategies employed in several urban areas and discuss how geospatial technologies might be used to improve understanding of human vulnerabilities to extreme heat in urban environments and enhance hazard mitigation. A conceptual framework for designing geospatial information infrastructure for the extreme heat impacts mitigation is presented.

Heat Waves and Their Impacts

Heat-related mortality and morbidity in the United States indicate continuing vulnerability of urban populations to extreme heat. The National Weather Service Office of Climate, Water, and Weather Services estimates that a total of 2,248 people throughout the United States lost their lives due to extreme heat between 1986 and 2000 (Fig. 1).

Exposure to extreme heat events can cause a myriad of health conditions due to vital fluid and mineral loss in the body. Heat stroke can become life threatening within minutes and occurs when body temperature rises above 105°F (40.6°C) (Center for Disease Control (CDC) 1995). Compared to other meteorological hazards, which pose threats to property and human health (e.g., floods, hurricanes, and tornadoes), heat waves rank first as the cause of human mortality. Table 1 summarizes economic losses and deaths due to a variety of hazards that occurred in the U.S. between 1996–2000 (National Weather Service 2001). Although not intuitive, heat waves (here shown in concurrence with droughts) resulted in the largest number of deaths in the United States in this class of natural disasters. The complexity of heat-wave hazards derives from the fact that unlike most natural haz-

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Note. Discussion open until January 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on May 10, 2002; approved on April 19, 2004. This paper is part of the ***Natural Hazards Review***, Vol. 5, No. 3, August 1, 2004. ©ASCE, ISSN 1527-6988/2004/3-147–158/$18.00.

Nat. Hazards Rev., 2004, 5(3): 147-158

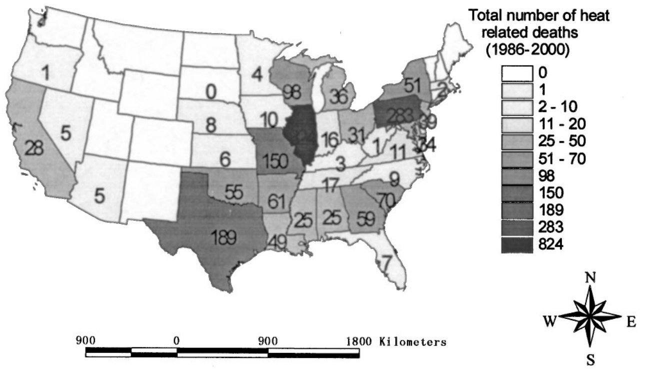

Fig. 1. Spatial distribution of heat related mortality from 1986 to 2000. Mortality statistics were obtained from the National Weather Service Office of Climate, Water and Weather Services.

ards the climatological indicators of heat hazard vary between different regions. Also, the absence of common definitions and criteria for heat hazard identification may contribute to delayed actions in response to an already established heat wave. Heat waves are sporadic phenomena, occurring throughout the United States. Frequency, intensity, and duration of heat waves, however, vary drastically from year to year. In the United States, there is no single universal threshold temperature above which the rate of heat-related morbidity and mortality increase sharply. Instead, tolerance of excess heat varies regionally according to the population and its preparation for hot weather and according to the local average temperatures and frequency of extreme temperatures (McMichael et al. 1996).

The magnitude of morbidity and mortality attributed to excessive heat exposure is most likely underestimated. This underestimation can be attributed to the lack of standardized definitions of heat-related mortality and resulting misclassification of cases. Heat can exacerbate existing medical conditions, which contribute to the cause of death. However, several studies showed that some cases of illnesses and deaths resulting from multiple causes (including heat as one of the contributing factors) were only attributed to preexisting medical conditions (Oechsli and Buechley 1970; Schuman 1972; Bridger et al. 1976; Kalkstein 1995; Semenza 1996). The effects of heat waves can be seen in increased mortality the day after the high temperatures occur (Kalkstein 1991). During a July 1988 heat wave in Allegheny County, Pennsylvania, excess mortality was correlated with the average temperature of the previous day, signifying that consecutive high day and night temperatures caused the heat-related mortality and morbidity among sensitive populations (Ramlow and Kuller 1990).

Table 1. Summary of Monetary Losses, Morbidity, and Mortality for Major Natural Hazards Occurred in the U.S. from 1996–2000 (NWS 2001)

Natural hazard	Monetary loss (Millions of dollars)	Morbidity	Mortality
Drought/heat wave	2,200	3,238	950
Tropical cyclone (tropical storm/hurricane)	12,400	141	66
Tornado	5,600	6,136	345
Flooding	15,900	7,408	490
Lightning	190	1,505	235
Winter storms	1,800	2,017	318
Extreme cold	1,400	99	146

Originally it was thought that the single predictive meteorological variable for increased mortality during a heat wave was temperature (Oechsli and Buechley 1970). Now it is known that a variety of meteorological variables contribute to human illnesses and deaths during heat waves. These variables include relative humidity, wind speed, and fluxes in both short- and long-wave radiation, in addition to temperature (Steadman 1984). The ‘‘heat index’’ is a combination of these factors and is used to evaluate heat stress on the human body. One problem with the heat index rating is that it is the same across the world, with no adjustment for differing climates in various regions. For instance, 95°F (35°C) might be considered ‘‘normal’’ in Houston, Texas and extremely hot in a more temperate climate, such as New York City.

Urbanization is one of the risk factors contributing to heat-wave impacts on humans. Heat-related illnesses and deaths are a greater problem in cities than in suburban or rural areas, because the combined effect of high temperature and high humidity are more intense in the centers of urban areas. In a study of the July 1966 heat wave in New York City and St. Louis, Missouri, Schuman (1972) discovered that areas of cities with more concrete and less vegetation exhibited higher mortality rates due to heat-related illnesses. Further study on this same extreme temperature event revealed a positive correlation between higher temperature and population density during this heat wave in the New York–New Jersey metropolitan area, leading to a mortality rate 55 times greater in the city, as opposed to rural areas (Buechley et al. 1972). Urban settings often include high-rise apartment buildings, and people residing in the top floors of such buildings are at a greater risk (Barrow and Clark 1998).

Examples from the literature showed that heat waves have a more pronounced effect on the population of temperate climates, and that health impacts are unevenly distributed over the course of the warm season. During July 1993, the city of Philadelphia exhibited 118 heat-related deaths (CDC 1994). Another high-mortality heat wave occurred in Chicago in mid-July 1995. Over 500 people died in the heat wave, which lasted only 3 days. The high number of deaths was primarily due to high day and night-time temperatures that lasted for 48 h (Karl and Knight 1997). In addition to high nighttime temperatures, which did not allow the body to recover from extreme heat during the day, both Chicago and Philadelphia are in temperate regions that do not experience as many high-temperature episodes as the southwestern United States for instance. Increased mortality due to heat waves has been linked to regions that experience greater summer weather variations, such as New York City and Chicago, as opposed to Houston and Los Angeles (Greene and Kalkstein 1996; CDC 1984; CDC 1994). People who live in persistently hot regions of the world acclimate to the higher temperatures and adapt more easily, compared to those who live in a region that is usually colder and less oppressive. Davis et al. (2001) analyzed mortality data for over 25 years and concluded that excess summer mortality in the U.S. has occurred in most northern cities, but there was little or no mortality response to high apparent temperatures in southern cities, regardless of the severity of the extreme heat event.

Heat waves that occur earlier in the summer usually exhibit higher mortality rates as well, primarily because the human body has not had time to acclimate to the inclement climate (McMichael et al. 1996). In addition, the most susceptible portion of the population would be affected by an extreme event early in the summer season, resulting in a phenomenon often called mortality displacement (Kalkstein 1995). This means that people were likely to die from other causes and that the heat wave caused death a little sooner, resulting in a lower mortality rate during extreme events later in the summer. This can be explained with the concept of competing causes, which refers to the multiple potential causes of death, whereby one cause (e.g., extreme heat) supercedes another (e.g., an illness) thus causing an earlier than anticipated death (Rothman and Greenland 1998). Overall, the factors that most affect the rate of mortality include the duration and timing of a heat wave, and also the geographical location and expected exposure to heat in a certain region.

In the next several decades, the reinforcing effects of global warming and continued urbanization could result in even more catastrophic human health impacts in the U.S. In order to assess the potential effects of global warming on large U.S. cities, with a population greater than 1 million, Kalkstein and Greene (1997) developed a novel air mass-based synoptic approach to determine a relationship between climate change and heat-related mortality in large cities. In the current climate, two air masses dominate the increase in mortality in midwestern and eastern cities during the summer season. General circulation models were used to predict the change in frequency and intensity of the air masses that cause increased heat-related mortality. If the climate warms as the models predict, summer deaths will increase substantially, and although winter deaths will decrease slightly, this will not be enough to offset the amplification of summer mortality.

Characterizing Urban Heat Islands

The local-to-regional influence of cities on climate is well documented by more than a century of observational, modeling and laboratory studies that have compared weather and climate parameters in urban environments to nearby rural areas. As urban populations grow, ever increasing attention is being directed to various climatological and environmental issues associated with urban development, including the urban heat island effect (American Meteorological Society 2000). The term ‘‘urban heat island’’ has been used in climate research primarily to describe differences in background surface temperature between urban areas and rural surroundings. Urban heating is largely attributed to excess heat absorbed and released from urban infrastructure, such as buildings, streets, and parking lots (Kim 1992). A temperature gradient between an urban area and nearby rural land can often reach up to 10°C.

Quantitative studies of the urban influence on near-surface air temperatures have been ongoing for almost 2 centuries (e.g., Howard 1833; Sunborg 1950; Duckworth and Sandburg 1954; Mitchell 1961; DeMarrais 1961; Chandler 1965; Gallo and Owen 2000). Books describing and analyzing the impacts of cities on local climate have been written by Howard (1833); Chandler (1965); Oke (1978); Landsberg (1981), and others. Several review papers summarize the first generation of urban climate studies (Lowry 1967; Landsberg 1970; Landsberg 1981). From these studies it was clear that land use change, particularly the development of built infrastructure, could significantly alter temperatures, humidity, winds, visibility, radiation, and other meteorological parameters in urban areas and that heat stress in cities would typically exceed the heat stress experienced in surrounding rural areas. The influence of the building infrastructure and nonnatural surfaces characteristics was clearly detectable at a variety of local time (e.g., differences in the diurnal temperature gradient) and space (e.g., changes in surface characteristics across an urban area) scales. Oke (1997) estimated typical differences in meteorological and climatological parameters between a rural area and a mid-latitude city with about 1 million inhabitants. Examples of these differences are shown in Table 2.

Table 2. Selected Typical Urban Climate Effects and Surface and Atmospheric Properties for a Midlatitude Cty with about 1 Million Inhabitants. Modified from (Oke 1997)

Variable	Change	Magnitude of change or comment
Air temperature	Warmer	1–3°C per 100 years; 1–3°C annual mean; up to 12°C hourly mean (summer daytime)
Humidity	Drier	Summer daytime
	More moist	Summer night, all day winter
Heat storage	Greater	About 200%
Wind speed	Decreased	5–30% at 10 min strong flow
	Increased	In weak flow with heat island
Cloudiness	More haze	In and downwind of city
	More cloud	Especially in lee of city
Property	**Change**	**Typical magnitude**
Albedo	Lower	Rural: 0.12–0.20 Suburban: 0.15 Urban: 0.14
Anthropogenic heat	Greater	Rural: absent Suburban: 15–50 $\mathrm{W\,m^{-2}}$ Urban: 50–100 $\mathrm{W\,m^{-2}}$ (winter up to 250 $\mathrm{W\,m^{-2}}$)

The causes of the urban heat island can be related directly to the integrated effects of the net albedo (reflectivity) of the urban surface (Taha et al. 1988), the thermal storage capacity of the urban physical infrastructure and remaining natural ecosystems (Myrup 1969, Atwater 1972), gaseous and particulate air pollutants, and the interaction of boundary layer winds with topography and infrastructure (Oke 1997). Thermal storage of heat in building materials is an important consideration in the urban energy balance and in mitigation of hot season human health impacts. Many materials used for the construction of buildings and streets will store heat more effectively than did the natural ecosystems they replace. That energy is released slowly at night, accentuating the nighttime urban heat island (Akbari et al. 1989). The process of heat storage in the infrastructure also delays daytime temperature rise and shifts the time of peak cooling demand depending on the number of consecutive days of a particular weather pattern.

The distribution of vegetation is also important because latent heat loss from evapotranspiration decreases the energy available for heating the near-surface air. Differences in the amount of vegetation cover in a city can influence the urban-rural gradient by as much as 8–10°C. Reducing vegetation cover lowers evapotranspiration, and, consequently, more energy goes into sensible heat flux and thermal storage (Nunez and Oke 1977).

Vulnerable Populations

Societal vulnerability often determines the severity of impacts of a natural hazard on an individual or a group. A number of case studies used epidemiological and statistical techniques to understand the relationship between heat waves, heat-related morbidity, and mortality and to identify vulnerable groups of people

(Smoyer 1998; Kalkstein and Greene 1997; Chan et al. 2001). In the natural hazards research literature, many authors have discussed factors contributing to vulnerability (Downing 1991; Dow 1993; Blaikie et al. 1994; Cutter 1996; Morrow 2000). Among these factors are characteristics of the environment, individuals (e.g., special needs population, poverty/wealth indicators, gender, and race), and society. Specific studies of heat waves and associated mortality and health impacts have identified characteristics of vulnerable populations. The increase in mortality during heat waves rests disproportionately on such segments of the population as the elderly, newborn babies, young children (less than 4 years old), infirm (e.g., people with cardiovascular disease), poor, socially isolated, and people with mental disabilities (Ellis 1972; Schuman 1972; Bridger et al. 1976; Jones et al. 1982; Bross et al. 1994; McMichael 1996; Batscha 1997; How et al. 2000; McGeehin and Mirabelli 2001).

The body's ability to regulate temperature is hampered by old age, obesity, heart disease, poor circulation, and certain medications. As opposed to healthy people, individuals with these conditions do not exhibit the same ability to thermoregulate their body through radiation and evaporative heat loss when exposed to high temperature and elevated humidity (CDC 1996) and often do not have the mobility to leave their hot residence for a cooler locale.

Living conditions and social networks also contribute to overall vulnerability to extreme heat (McGeehin and Mirabelli 2001). A significantly higher death rate occurred for people living in nursing homes without air conditioning, as opposed to those with artificial cooling systems during heat waves in New York City in 1972 and 1973 (Marmor 1978). The elderly, in general, was the most vulnerable age group during extensive heat waves in New York City during August 1975 and June 1984 (Ellis and Nelson 1978; CDC 1984). The high mortality rate was attributed to those people who lived at home and took care of themselves, as opposed to those who stayed in nursing homes or hospitals during the extreme event. Also, the elderly and infirm are more at risk if they are confined to their bed or unable to care for themselves, incapable of leaving home each day, or live alone, as was determined by a study on the Chicago heat wave of July 1995 (Semenza et al. 1996). This risk decreases if they have a social network of friends or family in the neighborhood, air conditioning, and access to transportation.

The poor are another vulnerable group in the context of heat waves. This group often lacks access to an air conditioner or a means of transportation to go to a cooler location and often lives in city centers, where the effect of the urban heat island is the most pronounced (Schuman 1972; Jones et al. 1982; Smoyer et al. 2000). During extended heat waves, the lack of nocturnal cooling can have a particularly devastating impact on morbidity and mortality, especially in urban high-rise buildings, which are susceptible to heat island effects. Homes located in high crime rate areas are also more vulnerable, because people are often afraid to leave windows open at night, which would increase air circulation indoors.

With the changing demographics in the U.S., there has been increased attention in the natural hazards field to the vulnerability of racial and ethnic communities (Perry et al. 1983; Fothergill et al. 1999). A lower preparedness level, language barriers, and socio-economic factors such as income, housing issues, and availability of quality health care, may contribute to increased vulnerability of racial and ethnic communities to the impacts of heat waves.

Reducing Heat Wave Mortality and Morbidity

Existing Mitigation Strategies

Following major heat waves in the 1990s, several warning systems were implemented in places with high heat-related mortality rates. Kalkstein et al. (1996) developed a Health Watch/Warning System for Philadelphia, in order to identify approaching heat waves and warn vulnerable populations about those hazardous weather events. This system is based on a synoptic climatological approach by grouping days with homogeneous meteorological conditions such as temperature, humidity, cloud coverage, wind speed, and other variables and comparing these to heat wave episodes in the past that have caused high mortality events. For example, in Philadelphia there is a strong correlation between certain excessively hot and humid maritime air masses and mortality. When one of these air masses is forecast (up to 48 h in advance), the city health commissioner consults with the Philadelphia Department of Public Health and the National Weather Service and issues special health advisories. Health advisories are accompanied by media broadcasts, a telephone-based ''heatline,'' and the implementation of a ''buddy system,'' which encourages neighbors to check on susceptible individuals, such as elderly or ill people on their street. Also, local utilities are encouraged not to interrupt service during the heat emergency. A similar study was developed for five major Australian cities, correlating temporal synoptic indices and past heat-related mortality data to identify dangerous air masses (Guest et al. 1999).

A different type of weather warning system that depends on the comparison of a weather stress index (WSI) with mortality rates has been developed in Hong Kong (Li and Chan 2000). The WSI compares the apparent temperature with the mean value for that date and location. The apparent temperature adjusts the ambient temperature according to relative humidity and human perception (Steadman 1979). If the WSI is particularly high, meaning an increased mortality rate occurred during similar weather conditions in the past, then the public is warned about possible extreme weather conditions. In addition, precautionary measures that the public can take to reduce their risk are included with the warning.

Community-based outreach programs can be especially effective in reaching vulnerable populations and helping them to protect themselves during extreme heat waves. The Medical College of Pennsylvania developed a community-based assessment of isolated, older adults (65 years and older) in northern Philadelphia to determine their vulnerability and knowledge of heat-related illnesses (Mattern et al. 2000). They discovered that one-on-one intervention is the most effective approach to reducing heat-related health threats. In addition, they found that health-related materials should be designed for older adults, such as an easily readable thermometer and other materials designed with cultural and age-specific characteristics.

After an intense heat wave in St. Louis in 1980 resulted in the hospitalization or death of one in every 1,000 residents due to heat-related illnesses (Jones et al. 1982), the city developed a Heat Wave Mortality Prevention Program (Smoyer 1998). This involved the implementation of a heat wave health watch/warning system, public education about health risks, development of cooling shelters, and the distribution of air-conditioners to high-risk populations. The efficacy of the program has not been evaluated to determine whether it actually deters excess mortality rates during high temperature episodes. The number of people at risk in

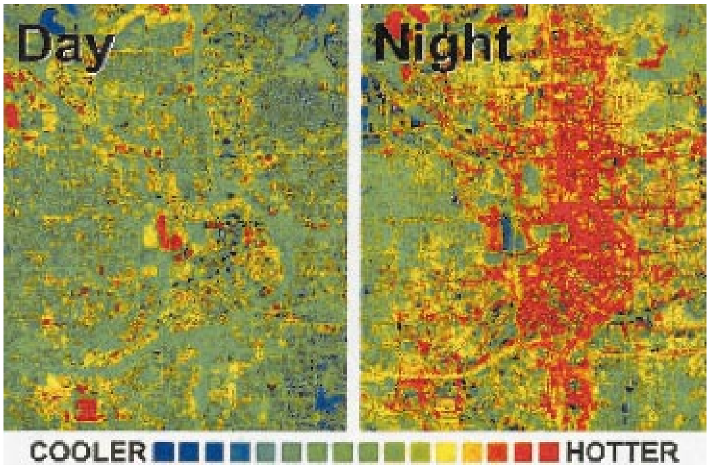

Fig. 2. (Color) Thermal infrared aircraft data provide comparison of nighttime and daytime surface temperatures in downtown Atlanta (Data source: NASA Marshall Space Flight Center).

the city has actually increased between 1980 and 1995 due to economic decline.

After the 1995 heat wave, the city of Chicago developed an Extreme Weather Operations Plan, which included mitigation measures to reduce impacts of heat waves on the city's population. After receiving a heat warning from the National Weather Service, the Chicago Fire Commissioner mobilizes the city social service departments to carry out well-being checks, provide cooling centers, check buildings for proper ventilation, monitor nursing homes and hospital emergency rooms, watch for citizens at risk from excessive heat exposure, and distribute ''Heat Tips'' brochures with information about how to stay healthy during a heat wave. During the consequent heat wave event in 1999, the death toll from the heat in Chicago was reduced by 80% compared to the 1995 heat wave. The reduced impacts were partially due to meteorological differences between the two heat waves (e.g., lower intensity and longer warm onset of the latter), but largely because of improved preparedness and timely responsiveness of municipalities (Palecki et al. 2001).

In 2002, the National Oceanic and Atmospheric Administration (NOAA) launched a new early heat warning system, which can provide local emergency officials with advanced warning of prolonged periods of extreme heat up to 7 days before their onset. The early warning system uses the daily mean heat index, which incorporates information on both nighttime lows and daytime highs and is calculated by using the forecasted values of minimum and maximum temperature and relative humidity (NOAA 2002).

Role of Geospatial Technologies

The potential for effective applications of geospatial technologies to disaster mitigation is closely linked to the predictability of the events in time and space and their consequences (Alexander 1991). Extreme heat events are a complex, subtle, and deadly threat compared to most other natural hazards. Yet, heat waves are more readily forecast and more amenable to actions that can prevent or mitigate human health impacts. The continuing development of geospatial technologies provides increasingly sophisticated, yet flexible tools for data collection, analysis, monitoring, mapping, management, and communication to the public. The use of geospatial technologies, including geographic information systems (GIS) and remote sensing, is increasing in many sectors of society, including meteorology and climatology, urban planning, and disaster management. Successful implementation of these technologies in various sectors and disciplines, such as medical geography, hazard management, and urban planning, allows us to believe that technological capability to mitigate risk of urban heat impacts exists. However, no comprehensive methods have been developed for utilizing geospatial technology in the mitigation of the impacts of extreme heat on an urban population. Studies of urban heat islands, vulnerability assessment, and community-based hazard mitigation could benefit from applications of remote sensing and GIS. In the following sections, benefits and limitations of remote sensing and GIS technologies are discussed in the context of heat wave impact mitigation and the writers' proposed conceptual framework.

Remote Sensing

The spatial nature of land surface air temperatures from urban to regional scales has been studied with direct ground-based meteorological monitoring, remote sensing from airborne and satellite platforms, and computer modeling methods. Each of these methods for measuring, forecasting, and simulating temperatures or heat stress index has associated uncertainties and limitations. The writers focus on the specific type and quality of information that can aid in the mitigation of heat wave impacts on vulnerable urban populations.

One application of remote sensing observations is thermal mapping. Emitted ''heat'' energy from objects on the earth and from the earth surface itself can be sensed through the windows at 3 to 5 μm and 8 to 14 μm of the electromagnetic spectrum, using airborne or spaceborne thermal scanners (Lillesand and Kiefer 1994). Fig. 2 illustrates an example of thermal remote sensing applied in a study of an urban heat island. High-resolution thermal infrared aircraft data show the distinction of nighttime and daytime surface temperatures in downtown Atlanta, clearly indicating an urban heat island effect. The nighttime data reflect the differential cooling rates associated with soils and vegetation compared to the heat storage associated with built infrastructure. The daytime data illustrate more uniform surface temperatures across the landscape due to direct radiation, active mixing by surface winds, and the diminished influence of heat storage.

Satellite and airborne remote sensing techniques can provide relatively frequent and synoptic coverage of urban versus rural temperature variations and detect spatial variability within urban

Table 3. Selected Satellite and Airborne Sensors with Potential Use for Heat Detection

Thermal band number	Bandwidth (μm)	Spatial resolution (m)	Temporal resolution
Landsat Thematic Mapper (TM) on Landsat 4 and 5			
6	10.4–12.5	120×120	16 days
Landsat Enhanced Thematic Mapper (ETM+) on Landsat 7			
6	10.4–12.5	60×60	16 days
NOAA AVHRR			
3	3.55–3.93	1100×1100	Daily (every 12 hours)
4	10.3–11.3	1100×1100	
5	11.5–12.5	1100×1100	
NASA Thermal Infrared Multispectral Scanner (TIMS) (airborne)			
1	8.20–8.6	Variable (IFOV=2.5 mrad)	Variable
2	8.6–9.0		
3	9.0–9.4		
4	9.4–10.2		
5	10.2–11.2		
6	11.2–12.2		
Terra ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)			
10	8.125–8.475	90×90	Daily
11	8.475–8.825	90×90	
12	8.925–9.275	90×90	
13	10.25–10.95	90×90	
14	10.95–11.65	90×90	
MODIS (Moderate Resolution Imaging Spectrometer)			
20	3.660–3.840	1000×1000	Daily
21	3.929–2.989	1000×1000	
22	3.929–2.989	1000×1000	
23	4.020–4.080	1000×1000	
31	10.780–11.280	1000×1000	
32	11.770–12.270	1000×1000	
Multispectral thermal imager			
15 bands			
Visible		5×5	Variable
Other		20×20	

heat islands. Lo et al. (1997) studied the urban heat island in Huntsville, Alabama, using high-resolution thermal infrared imagery from the NASA Advanced Thermal and Land Applications Sensor (ATLAS) system. Satellite data provided accurate characterization of the urban land cover types for the spatial modeling of the urban heat island effect. Aniello et al. (1995) used Landsat Thematic Mapper data and a GIS to map microurban heat islands in a portion of Dallas. The results of the study showed that the temperature of microurban heat islands was 5–11°C higher compared to surrounding areas by midmorning. Ben-Dor and Saaroni (1997) found airborne video thermal radiometry to be an effective and low-cost tool for detection and monitoring of microscale structures of the urban heat island.

Remote sensors used in various studies differ in terms of their spectral, spatial, and temporal resolutions, and their use depends on a particular research task. Table 3 shows characteristics of the selected satellite and airborne sensors that can operate in the thermal portion of the electromagnetic spectrum and, therefore, have potential in applications of urban heat detection and monitoring. There are also an increasing number of commercially available sensors (not included in Table 3), which can operate from satellites, aircrafts, and helicopters. For example, the Vid/Thermal Tracker 2000 (AVCAN Systems Corporation, Vancouver, BC) provides a helicopter-based technology that is able to accurately measure points of interest within an accuracy of 1 m and 0.2°C temperature. Originally designed to provide information for major industries, this technology can be utilized in urban heat island mapping.

There have been significant advancements in remote sensing technology, as indicated by the studies of the urban heat island discussed previously. However, many limitations still exist, especially for the health applications of remote sensing. According to Vicente and Maynard (2002), limiting factors include lack of appropriately high spatial, temporal, and spectral resolution of existing sensors and the absence of continuous temporal and spatial data sets required for the study of specific health-related problems. In addition, the high cost of high-resolution remote sensing data, differences in data formats, and poor technology transfer methods often limit integration of remote sensing and health data. Many of these issues are being addressed as new satellites are being developed and launched. However, there is still a need for improvement of communication between data providers and the users, as well as a need for user-friendly, operational, and low-cost decision-support systems.

Geographic Information Systems

A geographic information system is an invaluable tool for integration, analysis, and visualization of spatial information. GIS presents a set of concepts, methods, and tools to explore spatial patterns in data. Geospatial databases could help bring multiple datasets together for comprehensive analysis of a research question or practical application. Although GIS as a technology is well developed and has been widely used in urban planning, disaster management, and various environmental applications, researchers only recently started to use GIS in studies of human health, (Gatrell and Loytonen 1998) meteorology, and climatology (Shipley et al. 2000; Wilhelmi and Brunskill 2003).

Environmental epidemiology is one of the fields where GIS, remote sensing, and health research have come together. Examples can be found in research on infectious and vector-borne disease surveillance (Glass et al. 1995; Kitron et al. 1994; Richards 1993), exposure assessments (Wartenberg 1992; Hjalmars et al. 1996; Holm et al. 1995), identification of study populations (Croner et al. 1996), disease mapping (Jacquez 1998; Xue et al. 1999), and public health surveillance (Rushton 1998).

The spatial characterization of risk and vulnerability factors in GIS is a key step for hazard mitigation. In an earlier study, Martinez et al. (1989) used the county-level dot mapping technique to show fatalities due to extreme heat among elderly persons. This technique helped to identify high-risk areas of the continental U.S. in which severe adverse health impacts are likely to occur. Improvements in GIS technology have allowed for easier integration of biophysical and socioeconomic data and have led to an increased number of studies on assessment of spatial risk and vulnerability and disaster management (Dangermond 1991; FEMA 1994, 1996; Cova and Church 1997; NOAA Coastal Service Center 1999; Cutter et al. 2000; Wilhelmi and Wilhite, 2002).

A number of limitations still exist in successful applications of GIS to heat wave impact mitigation. Some of these limitations include (1) existing GIS are limited in their ability to represent the spatiotemporal dynamics of natural phenomena; (2) there is a lack of data sharing among public and private agencies, organizations, and government sectors; (3) social, economic, and demographic data are often presented in a census unit form, which makes it

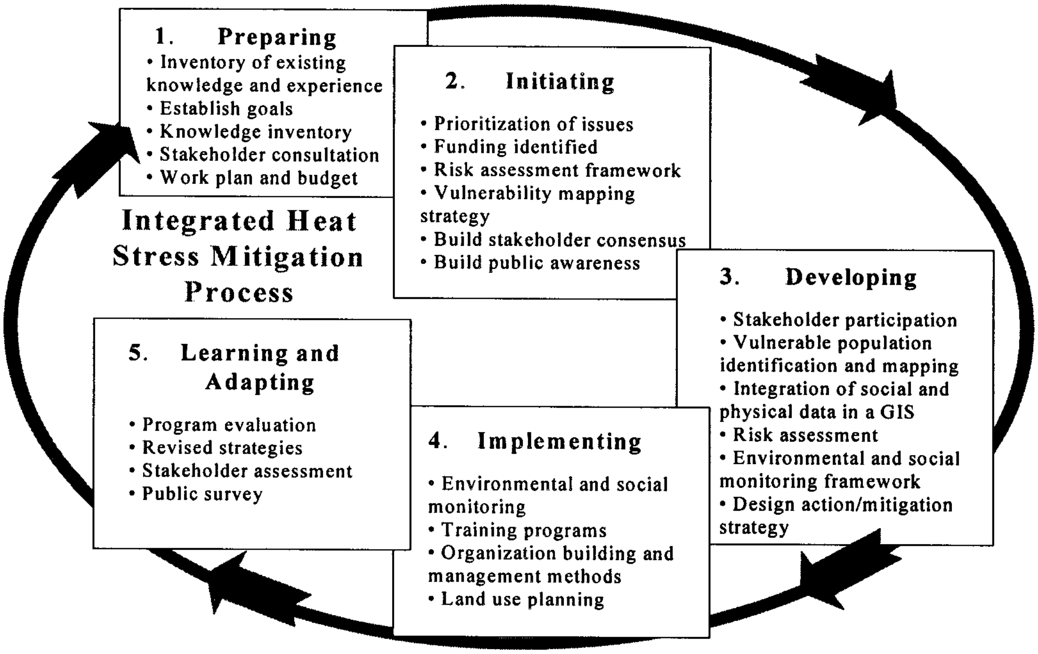

Fig. 3. Integrated heat-wave mitigation process

difficult to pinpoint the most vulnerable households; (4) often there are differences in scale and resolution between social and environmental data; (5) cost of GIS software could be a limiting factor to some organizations; and (6) lack of human resources to timely process and map data. Many of these factors are being addressed with the advancements in GIS science and technology.

Conceptual Framework for Mitigating Heat-Wave Impacts

The literature review showed that impacts of extreme heat largely depend on geographic location, characteristics of an urban environment, and human vulnerabilities, in addition to meteorology and climatology of heat waves. The environmental and social factors of vulnerability to heat-related morbidity and mortality change in time and vary between different geographic locations, even within one neighborhood. In addition, anthropogenic climate change is generally expected to increase the frequency, duration, and severity of heat-stress conditions in many regions. Therefore, effective mitigation of a heat-wave hazard should be viewed as a continuing process with frequent updates on social, climatological, and environmental factors contributing to the overall risk.

An illustration of a heat-stress mitigation process is shown in Fig. 3. This framework emphasizes continuous learning through integration and updating of existing knowledge related to social changes, vulnerabilities, adaptations, and the lessons learned from previous heat-wave events. Such a process includes five major steps: preparing, initiating, developing, implementing, and learning and adapting. The first step is built upon previous experiences and events, including inventory, assessment, and analysis of historical heat-stress impacts and community responses. Goals and mitigation actions are identified through the stakeholders' involvement early in the process. The second and third steps focus on risk analysis, incorporating all known factors of heat-related health impacts, and loss of human life. The implementation stage includes environmental and social monitoring, developing a heat-resistant urban landscape, and building networks in communities and organizations. The last stage of the process evaluates overall strategies and addresses "lessons learned."

Because of the spatial nature of information required for development and implementation of the heat-wave mitigation process framework, geospatial technologies will play a major role in data management, analysis, and decision support. Fig. 4 illustrates details for how remote sensing and GIS will aid in the heat-stress mitigation process in general and in risk analysis in particular. In this model, the risk of a heat wave hazard is determined by the level of exposure to extreme heat, the current state of societal vulnerability, as well as the cases of previous heat-wave impacts.

The heat-stress cases and underlying factors of exposure and vulnerability should be identified first. For example, cases would include mortality and morbidity data, where extreme heat was either the primary or secondary cause in human death or illness. Duration, intensity, and timing of the heat wave are among the exposure factors affecting human death and illness from the extreme heat. The literature also emphasized that spatial patterns of temperature in urban areas could be significantly influenced for example by urban design, vegetation type and patterns, and the albedo of both natural and built surfaces. (Myrup 1969; Atwater 1972; Kim 1992; Oke 1997). Vulnerability largely depends on characteristics of individuals (e.g., special needs population, poverty/wealth indicators, gender, and race), and society. Understanding the relative importance of each of these components is crucial to developing a mitigation strategy for urban heat islands. The factors listed in Fig. 4 may vary between different communities and geographical regions; therefore, community involvement discussed earlier (Fig. 3) is important.

GIS can be used to map out cases of heat-related illnesses and deaths. This information when combined in GIS with data on urban characteristics (often acquired through remote sensing techniques), societal vulnerabilities, and meteorological information, can be analyzed for spatial patterns and temporal trends. Such information is often distributed between the whole hierarchy of public and private agencies and organizations. GIS brings an op-

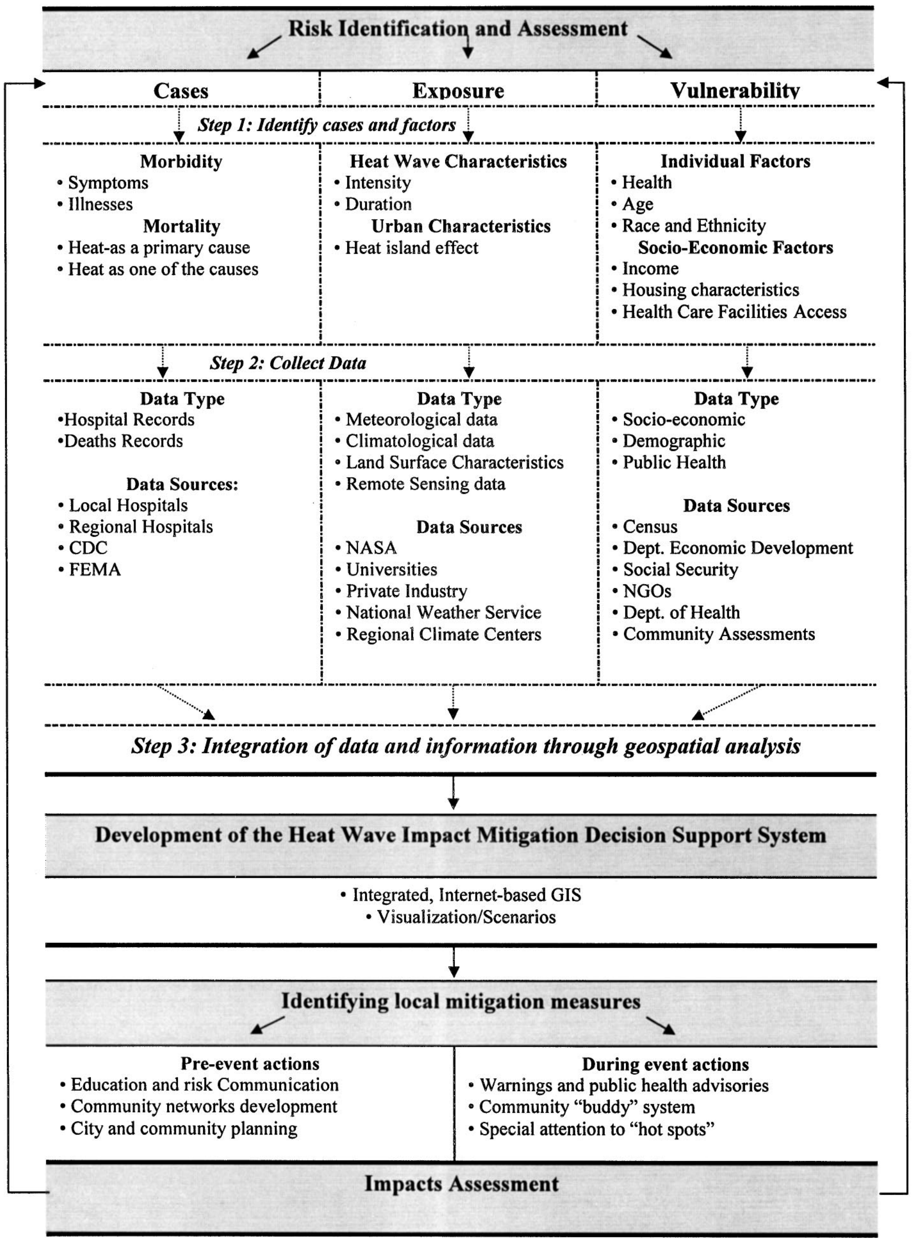

Fig. 4. Conceptual framework for urban heat-stress mitigation

portunity for an integrated new perspective to promote hazard mitigation and control of illnesses.

Identification of ‘‘hot spots’’ or high-risk zones within the urban area can lead to increased public awareness and more focused, location-specific mitigation measures. Many critical mitigation actions have been identified in numerous publications and public advisories. Effective implementation of those actions still remains a challenge for many U.S. urban communities, although significant progress has been made in recent years. Those steps include (but are not limited to) creating a ‘‘heat resistant’’ urban landscape (e.g., planting trees, replacing roof tops with lighter, more reflective materials), risk communication, and educational activities about protection of individuals from heat impacts, developing ‘‘buddy’’ systems among neighbors, designating cooling centers, transportation networks, and establishing heat forecasting and warning systems. Fig. 5 illustrates these mitigation measures and also shows a network of organizations responsible for implementation of these measures and means of information dissemination to the public. For example, creating a heat-resistant urban landscape will involve urban planners, landscape architects, and housing developers. Communicating risk to vulnerable populations, educating them about heat impacts, and establishing neighborhood ‘‘buddy systems’’ will be done through various media programs, visits from social workers, and community meetings.

Because most risk factors for heat-related illnesses are known, steps can be taken to prevent unnecessary morbidity and mortality for such susceptible populations. However, much better communication between both public and private service organizations will be required. For instance, Semenza et al. (1996) discovered that apartment dwellers have a lower rate of working air conditioners, as opposed to those who own their own home. The public social service agencies and private property management services need to share information on these types of vulnerabilities. It is important to establish these networks before a heat event so that

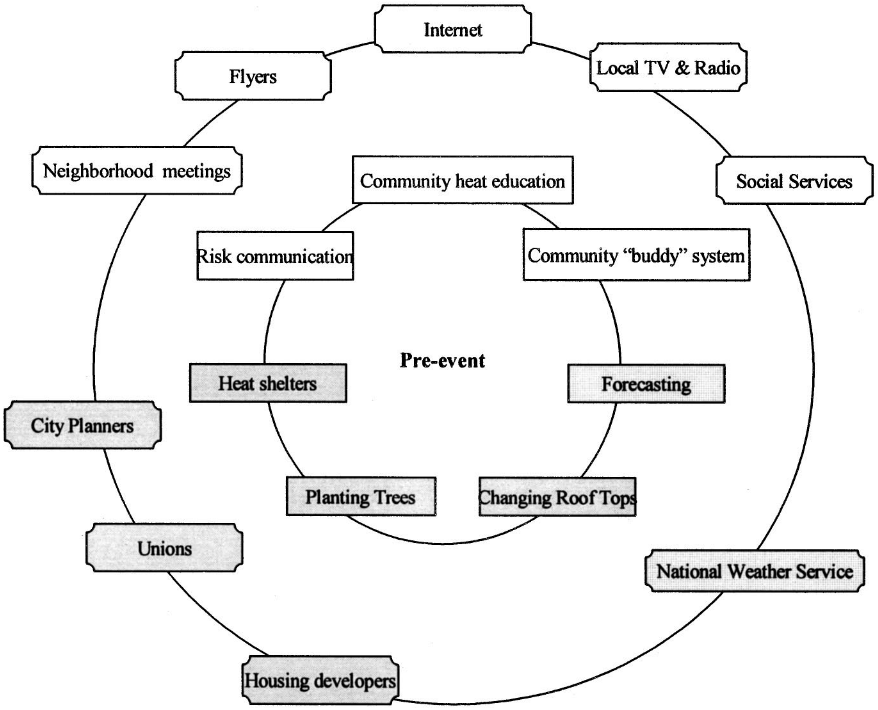

Fig. 5. Mitigation measures and informational networks relevant to heat-wave mitigation in urban areas.

once the heat warnings are issued, those individuals or communities most vulnerable can be reached without delays. Examples from Chicago (Palekie et al. 2001) and Philadelphia (Kalkstein 2000) indicate that improvements in understanding the physical and social system dynamics associated with heat-wave mortality and morbidity can be essential to advances in mitigation. Despite existing limitations, geospatial technologies can provide tools and methods that integrate information and catalyze collaborative efforts across disciplinary and organizational boundaries.

Collecting data and integrating data through geospatial analysis and designing decision support systems would largely rely on the availability of geospatial technologies and a data-sharing network of participating organizations. The feedback loop shown in Fig. 4 emphasizes that existing knowledge, perceptions, and data on heat-wave impacts, exposure, and vulnerability should be updated with changes in the environment and in society.

Future Trends and Concluding Remarks

In order to effectively mitigate the impacts of extreme heat, interdisciplinary background research, development and maintenance of extensive databases on both physical and social characteristics of the urban environment, and the active participation of many sectors and levels of municipalities and communities are needed.

Extreme heat is a complex natural hazard causing loss of human life and threats to human health. Global climate change introduces an uncertain factor into the heat-wave threat equation. Although temperatures are expected to rise, due to global warming, the question is when, where, and how much climate will change at local and regional scales. Local changes in the spatial and temporal characteristics of air temperature, humidity, and other variables will most likely differ for varying regions of the world.

Because of the uncertainty of extreme weather events that could develop with global climate change, heat-wave warning systems are being developed for many vulnerable cities around the world, such as Rome, Shanghai, Toronto, and other cities in the United States (Kalkstein 2000). These systems are created in collaboration with the World Meteorological Organization, World Health Organization, United Nations Environmental Program, United States Environmental Protection Agency, and the University of Delaware. The basic approach used is similar to the Philadelphia model. Further interdisciplinary research is needed to develop and integrate improved weather forecasting capabilities for extreme heat events, more sophisticated vulnerability assessments, and innovations in warning and response systems (Patz et al. 2000).

The challenge of making progress in mitigation of heat wave impacts will be exacerbated by current demographic trends. Continuing urbanization of the global population, a maturing of the age distribution in many nations, the evolution of a complex ethnic mosaic, and increasingly wide disparities tied to education and income are trends that can contribute to an increased threat of heat-related mortality and morbidity. These trends are all well documented in the United States (e.g., Frey et al. 2001). Effective mitigation of the vulnerability of the elderly and children to harm and loss from extreme heat will require significant improvements in understanding of the social, psychological, and physiological dimensions of exposure and response to threats. Ngo (2001) has discussed how the complex interactions of chronological age, gender, marital status, race, education, religion, socioeconomic status, and geographic locations can influence the vulnerability of elderly populations to natural disasters. Much more synthesis and systemic analysis is needed to prepare society for the warmer, more crowded world of the 21st century.

There is evidence that the series of deadly heat waves that have occurred in the U.S. in the 1990s stimulated several cities to work toward better preparedness and mitigation of extreme heat events (Palecki et al. 2001). Applications of geospatial technologies in mitigation and management of other natural hazards (e.g., wildfires, earthquakes, hurricanes) lead us to believe that mitigation of heat-wave impacts can be further improved with better understanding and integration of spatial and temporal information on urban heat island dynamics and vulnerable urban populations. The writers' review of existing technologies indicates capabilities for developing a technologically advanced system that can compliment existing meteorological methods for heat-wave detection and warning with risk analysis and mitigation planning. The framework proposed in this paper illustrates how remote sensing and GIS can provide additional data and tools for integrating and sharing information resources across the wide range of public and private stakeholder organizations with responsibilities for mitigation of heat-wave impacts.

Acknowledgments

This research was supported by funding from the National Science Foundation to the University Corporation for Atmospheric Research and National Center for Atmospheric Research. We thank S. McNeeley at NCAR and two anonymous reviewers for their valuable suggestions to the earlier versions of this manuscript.

References

Akbari, H., Garbesi, K., and Martien, P. (1989). ''Controlling summer heat islands.'' *Proc., Workshop on Saving Energy and Reducing Atmospheric Pollution by Controlling Summer Heat Islands*, Lawrence Berkeley National Laboratory, Univ. of California, Berkley, Calif.

Alexander, D. E. (1991). ''Information technology in real time for monitoring and managing natural disasters.'' *Prog. Phys. Geogr.,* 15(3), 238–260.

American Meteorological Society. (2000). *Proc. 3rd Symp. on the Urban Environment*, August 14–18, Davis, Calif., American Meteorological Society, Boston.

Aniello, C., Morgan, K., Busbey, A., and Newland, L. (1995). ''Mapping micro-urban heat islands using Landsat TM and a GIS.'' *Comput. Geosci.,* 21(8), 965–969.

Atwater, M. A. (1972). ''Thermal effects of organization and industrialization in the boundary layer: A numerical study.'' *Boundary-Layer Meteorol.,* 3, 229–245.

Barrow, M. W., and Clark, K. A. (1998). ''Heat-related illnesses.'' *Am. Fam. Physician,* 58(3), 749–756.

Batscha, C. L. (1997). ''Heat stroke. Keeping your clients cool in the summer.'' *J. of Psychosocial Nursing,* 35(7), 12–17.

Ben-Dor, E., and Saaroni, H. (1997). ''Airborne video thermal radiometry as a tool for monitoring microscale structures of the urban heat island.'' *Int. J. Remote Sens.,* 18(14), 3039–3053.

Blaikie, P., Cannon, T., Davis, I. and Wisner, B. (1994). ''*At risk: Natural hazards, people vulnerability, and disasters*,'' Routledge, London and New York.

Bridger, C. A., Ellis, F. P., and Taylor, H. L. (1976). ''Mortality in St. Louis, Missouri, during heat waves in 1936, 1953, 1954, 1955, and 1966.'' *Environ. Res.,* 12, 38–48.

Bross, M. H., Nash, B. T., and Carlton, F. B. (1994). ''Heat Emergencies.'' *Am. Fam. Physician,* 50(2), 389–396.

Buechley, R. W., Van Bruggen, J., and Truppi, L. E. (1972). ''Heat island = Death island?'' *Environ. Res.,* 5, 82–92.

Center for Disease Control (CDC). (1984). ''Heat-associated mortality—New York City.'' *MMWR Wkly.,* 33(29), 430–432.

Center for Disease Control (CDC). (1994). ''Heat-related deaths—Philadelphia and United States 1993–1994.'' *MMWR Wkly.,* 43(25), 453–455.

Center for Disease Control (CDC). (1995). ''Heat-related illnesses and deaths—United States 1994–1995.'' *MMWR Wkly.,* 44(25), 465–468.

Center for Disease Control (CDC). (1996). ''Extreme heat: A prevention guide to promote your personal health and safety,'' U.S. Dept. of Health and Human Services, Washington, D.C.

Chan, N. Y., Stacey, M. T., Smith, A. E., Ebi, K. L., and Wilson, T. F. (2001). ''An empirical mechanistic framework for heat related illness.'' *Clim. Res.,* 16, 133–143.

Chandler, T. J. (1965). *The climate of London*, Hutchinson & Co., London.

Cova, T. J., and Church, R. L. (1997). ''Modelling community evacuation vulnerability using GIS.'' *Int. J. Geograph. Inf. Sci.,* 11(8), 763–784.

Croner, C. M., Sperling, J., and Broome, F. R. (1996). ''Geographic information systems (GIS): New perspectives in understanding human health and environmental relationships.'' *Stat. Med.,* 15(17–18), 1961–1977.

Cutter, S. L. (1996). ''Vulnerability to environmental hazards.'' *Prog. Human Geogr.,* 20(4), 529–539.

Cutter, S. L., Mitchell, J. T., and Scott, M. S. (2000). ''Revealing the vulnerability of people and places: A case study of Georgetown County, South Carolina.'' *Ann. Assoc. Am. Geogr.,* 90(4), 713–737.

Dangermond, J. (1991). ''Application of GIS to the International Decade for Natural Disaster Reduction.'' *Proc., 4th Int. Conf. on Seismic Zonation*, Earthquake Engineering Research Institute, Stanford Univ., Palo Alto, Calif., 445–468.

Davis, R. E., Knappenberger, P. C., Novicoff, W. M., and Michaels, P. J. (2001). ''Decadal shifts in summer weather/mortality relationships in the United States by region, demography, and cause of death.'' *Proc. 14th Conf. on Biometeorology and Aerobiology*, American Meteorological Society, Boston.

DeMarrais, G. A. (1961). ''Vertical temperature difference observed over an urban area.'' *Bull. Am. Meteorol. Soc.,* 42, 548.

Dow, K. (1993). ''Exploring differences in our common future(s): The meaning of vulnerability to global environmental change.'' *Geoforum*, 23(3), 417–436.

Downing, T. E. (1991). ''Assessing socioeconomic vulnerability to famine: Frameworks, concepts, and applications.'' *Research Rep.* The Alan Shawn Feinstein World Hunger Program, Brown Univ., Providence, R.I.

Duckworth, F. S., and Sandburg, J. S. (1954). ''The effect of cities upon horizontal and vertical temperature gradients.'' *Bull. Am. Meteorol. Soc.,* 35(5), 198–207.

Ellis, F. P. (1972). ''Mortality from heat illnesses and heat-aggravated illness in the United States.'' *Environ. Res.,* 5, 1–58.

Ellis, F. P., and Nelson, F. (1978). ''Mortality in the elderly in a heat wave in New York City.'' *Environ. Res.,* 15, 504–512.

Fothergill, A., Meastas, E. G. M., and Darlington, J. D. (1999). ''Race, ethnicity, and disasters in the United States: A review of the literature.'' *Disasters,* 23(2), 156–173.

Federal Emergency Management Agency (FEMA). (1994). ''Assessment of the state of the art earthquake loss estimation methodologies.'' *FEMA-249*, FEMA, Washington, D.C.

Federal Emergency Management Agency (FEMA). (1996). ''HAZUS, the FEMA tool for estimating earthquake losses.'' *FEMA-287*, FEMA, Washington, D.C.

Frey, W. H., Abresch, B., and Yeasting, J. (2001). *America by the numbers: A field guide to the U.S. population*, The New Press, New York.

Gallo, K. P., and Owen, T. W. (2000). ''Seasonal trends in urban and rural temperatures of twenty-eight cities within the United States.'' *Proc. 3rd Symp. on the Urban Environment,* August 14–18, Davis, Calif. American Meteorological Society, Boston, 14–18

Gatrell, A.C., and Loytonen, M. (1998). *GIS and health*, Taylor and Francis, London.

Glass, G. E., Schwartz, B. S., Morgan, J. M., Johnson, D. T., Noy, P. M., and Israel, E. (1995). ''Environmental risk-factors for lyme-disease identified with geographic information systems.'' *Am. J. Public Health,* 85(7), 944–948.

Greene, J. S., and Kalkstein, L. S. (1996). ''Quantitative analysis of summer air masses in the Eastern United States and an application to human mortality.'' *Clim. Res.*, 7, 43–53.

Guest, C. S., et al. (1999). ''Climate and mortality in Australia: Retrospective study, 1979–1990 and predicted impacts in five major cities in 2030.'' *Clim. Res.*, 13, 1–15.

Hjalmars, U., Kullforff, M., and Gustaffson, G. (1996). ''Childhood leukemia in Sweden: Using GIS and spatial scan statistics for cluster detection.'' *Stat. Med.*, 15(7–9), 707–715.

Holm, D. M., Maslia, M. L., Reyes, J. J., Williams, R. C., and Aral, M. M. (1995). ''Geographic information systems: A critical resource in exposure assessment.'' *Superfund XVI Conf. and Exhibition Proc.*, 2, Washington, D.C., 860–866.

How, C.-K., Chern, C.-H., Wang, L.-M., and Lee, C.-H. (2000). ''Heat stroke in a subtropical country.'' *Am. J. Emerg. Med.*, 18(4), 474–477.

Howard, L. (1833). *Climate of London deduced from meteorological observations*, 3rd Ed., Harvey and Darton, London.

Intergovernmental Panel on Climate Change (IPCC). (2001). *Climate change 2001: The scientific basis*, J. T. Houghton, et al., eds., Cambridge University Press, New York.

Jacquez, G. M. (1998). ''GIS as an enabling technology.'' *GIS and health*, A. C. Gatrell, and M. Loytonen, eds., Taylor and Francis, London, 17–28.

Jones, T. S., et al. (1982). ''Morbidity and mortality associated with the July 1980 heat wave in St. Louis and Kansas City, MO.'' *JAMA, J. Am. Med. Assoc.*, 247(24), 3327–3331.

Kalkstein, L. S. (1991). ''A new approach to evaluate the impact of climate on human mortality.'' *Environ. Health Perspect.*, 96, 145–150.

Kalkstein, L. S. (1995). ''Lessons from a very hot summer.'' *Lancet*, 346, 857–859.

Kalkstein, L. S. (2000). ''Saving lives during extreme weather in summer.'' *Br. Med. J.*, 231, 650–651.

Kalkstein, L. S., and Greene, J. S. (1997). ''An evaluation of climate/mortality relationships in large U.S. cities and the possible impacts of a climate change.'' *Environ. Health Perspect.*, 105(1), 84–93.

Kalkstein, L. S., Jamason, P. F., Greene, J. S., Libby, J., and Robinson, L. (1996). ''The Philadelphia hot weather-health watch/warning system: Development and application, Summer 1995.'' *Bull. Am. Meteorol. Soc.*, 77(7), 1519–1528.

Karl, T. R., and Knight, R. W. (1997). ''The 1995 Chicago heat wave: How likely is a recurrence?'' *Bull. Am. Meteorol. Soc.*, 78(6), 1107–1119.

Kattenberg, A., et al. (1996). ''Climate models—projections of future climate.'' *Climate change 1995. The science of climate change*, J. T. Houghton, et al., eds., Cambridge University Press, New York.

Kim, H. H. (1992). ''Urban heat island.'' *Int. J. Remote Sens.*, 13(12), 2319–2336.

Kitron, U., Pener, H., Costin, C., Orshan, L., Greenberg, Z., and Shalom, U. (1994). ''Geographic information system in malaria surveillance—mosquito breeding and imported cases in Israel.'' *Am. J. Trop. Med. Hyg.*, 50(5), 550–556.

Landsberg, H. E. (1970). ''Man-made climatic changes.'' *Science*, 170(3964), 1265–1274.

Landsberg, H. E. (1981). *The urban climate*, Academic, San Diego.

Li, P. W., and Chan, S. T. (2000). ''Application of a weather stress index for alerting the public to stressful weather in Hong Kong.'' *Meteorol. Appl.*, 7, 369–375.

Lillesand, T. M., and Kiefer, R. W. (1994). *Remote sensing and image interpretation*, 3rd Ed., Wiley, New York.

Lo, C. P., Quattrochi, D. A., and Luvall, J. C. (1997). ''Application of high-resolution thermal infrared remote sensing and GIS to assess the urban heat island effect.'' *Int. J. Remote Sens.*, 18(2), 287–304.

Lowry, W. P. (1967). ''The climate of cities.'' *Sci. Am.*, 217(2), 15–23.

Marmor, M. (1978). ''Heat wave mortality in nursing homes.'' *Environ. Res.*, 17, 102–115.

Martinez, B. F., Annest, J. L., Kilbourne, E. M., Kirk, M. L., Lui, K.-J., and Smith, S. M. (1989). ''Geographic distribution of heat-related deaths among elderly persons.'' *JAMA, J. Am. Med. Assoc.*, 262(16), 2246–2250.

Mattern, J., Garrigan, S., and Kennedy, S. B. (2000). ''A community-based assessment of heat-related morbidity in north Philadelphia.'' *Environ. Res. Sec.*, 83, 338–342.

McGeehin, M. A., and Mirabelli, M. (2001). ''The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States.'' *Environ. Health Perspect.*, 109(2), 185–189.

McMichael, A. J., Haines, A., Slooff, R., and Kovats, S. (1996). *Climate change and human health*, World Health Organization, Geneva, Switzerland.

Mitchell, J. M.Jr. (1961). ''The temperature of cities.'' *Weatherwise*, 24(6), 224–230.

Morrow, B. H. (2000). Targeting households at risk for storms. *Storms*, R. A. Pielke Sr., and R. A. Pielke Jr., eds., Routledge, London.

Myrup, L. O. (1969). ''A numerical model of the urban heat island.'' *J. Appl. Meteorol.*, 8, 908–918.

NOAA Coastal Service Center. (1999). ''Community vulnerability assessment tool. New Hanover County, North Carolina case study.'' NOAA, Silver Spring, Md. ⟨http://www.csc.noaa.gov/products/nchaz/startup.htm⟩

NOAA National Weather Service Hydrometeorological Prediction Center. (2002). ''Mean heat index forecasts.'' NOAA, Silver Spring, Md. ⟨http://www.hpc.ncep.noaa.gov/heat_index.shtml⟩

National Weather Service, Office of Climate, Water, and Weather Services. (2001). ''Natural Hazard Statistics.'' ⟨http://www.nws.noaa.gov/om/hazstats.htm#⟩ (April 2001).

Ngo, E. B. (2001). ''When disasters and age collide: Reviewing vulnerability of the elderly.'' *Nat. Hazards Rev.*, 2(2), 80–89.

Nunez, M., and Oke, T. R. (1977). ''The energy balance of an urban canyon.'' *J. Appl. Meteorol.*, 16, 11–19.

Oechsli, F. W., and Buechley, R. W. (1970). ''Excess mortality associated with three Los Angeles September hot spells.'' *Environ. Res.*, 3, 277–284.

Oke, T. R. (1978). *Boundary layer climates*, Wiley, New York.

Oke, T. R. (1997). ''Urban climates and global environmental change.'' *Applied climatology: Principles and practice*, R. D. Thompson, and A. Perry, eds., Routledge, London, 273–287.

Palecki, M. A., Changnon, S. A., and Kunkel, K. E. (2001). ''The nature and impacts of the July 1999 heat wave in the midwestern United States: Learning from the lessons of 1995.'' *Bull. Am. Meteorol. Soc.*, 82(7), 1353–1367.

Patz, J. A., et al. (2000). ''The potential health impacts of climate variability and change for the United States: Executive summary of the report of the health sector of the U.S. national assessment.'' *Environ. Health Perspect.*, 108(4), 367–376.

Perry, R. W., Greene, M., and Mushkatel, A. H. (1983). ''American minorities in disasters.'' *Final Rep.*, Battelle Human Affairs Research Centers, Seattle, Wash.

Ramlow, J. M., and Kuller, L. H. (1990). ''Effects of the summer heat wave of 1988 on daily mortality in Allegheny County, PA.'' *Public Health Rep.*, 105(3), 283–289.

Richards, F. O. (1993). ''Uses of geographic information systems in control programs for onchocerciasis in Guatemala.'' *Bull. Pan Am. Health Organ.*, 27, 52–55.

Rothman, K. J., and Greenland, S. (1998). *Modern epidemiology*, 2nd Ed. Lippincott-Raven, New York.

Rushton, G. (1998). ''Improving the geographic basis of health surveillance using GIS.'' *GIS and health*, A. C. Gatrell, and M. Loytonen, eds., Taylor and Francis, London.

Schuman, S. H. (1972). ''Patterns of urban heat-wave deaths and implications for prevention: Data from New York and St. Louis during July, 1966.'' *Environ. Res.*, 5, 59–75.

Semenza, J. C., et al. (1996). ''Heat-related deaths during the July 1995 heat wave in Chicago.'' *N. Engl. J. Med.*, 335(2), 84–90.

Shipley, S. T., Graffman, I. A., and Ingram, J. K. (2000). ''GIS applications in climate and meteorology.'' *Proc., ESRI Annual User Conf.*, San Diego, ESRI, Redlands, Calif. ⟨http://www.esri.com/library/userconf/proc00/professional/papers/PAP159/p159.htm⟩

Smoyer, K. E. (1998). ''A comparative analysis of heat waves and asso-

Nat. Hazards Rev., 2004, 5(3): 147-158

ciated mortality in St. Louis, Missouri—1980 and 1995.'' *Int. J. Biometeor.*, 42, 44–50.

Smoyer, K. E., Rainham, D. G. C., and Hewko, J. N. (2000). ''Heat-stress-related mortality in five cities in Southern Ontario: 1980–1996.'' *Int. J. Biometeor.*, 44, 190–197.

Steadman, R. G. (1979). ''The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science.'' *J. Appl. Meteorol.*, 18, 861–873.

Steadman, R. G. (1984). ''A universal scale of apparent temperature.'' *J. Clim. Appl. Meteorol.*, 23, 1674–1687.

Sunborg, A. (1950). ''Local climatological studies of the temperature conditions in an urban area.'' *Tellus*, 2, 222.

Taha, H., Akbari, H., Rosenfeld, A., and Huang, J. (1988). ''Residential cooling loads and the urban heat island: The effects of albedo.'' *Energy Environ.*, 23(4), 271–283.

U.S. Census Bureau. (2000). ''Population projections.'' Washington, D.C. ⟨http://www.census.gov/population/www/projections/popproj.html⟩

Vicente, G. A., and Maynard, N. (2002). ''Integrated system for health applications of earth science remote sensing data.'' *Proc., IAPRS Commission II Symp.*, 36(2).

Wartenberg, D. (1992). ''Screening for lead exposure using a geographic information system.'' *Environ. Res.*, 59, 310–317.

Wilhelmi, O. V., and Brunskill, J. C. (2003). ''A meeting summary on a GIS in the Atmospheric Sciences.'' *Bull. Am. Meterol. Soc.*, 84(10), 1409–1414.

Wilhelmi, O. V., and Wilhite, D. A. (2002). ''Assessing vulnerability to agricultural drought: A Nebraska case study.'' *Natural Haz.*, 25(1), 37–58.

Xue, Y., Volz, P. A., and Cracknell, A. P. (1999). ''Human health applications of geographic information systems and remote sensing.'' *Michigan Academician XXXI*, 31, 325–344.